The Broad Line Regions of NGC 4151

I.Cassidy & D.J.Raine
Astronomy Group
University of Leicester, Leicester UK

Revised 17 July 1995
Accepted for publication in Astron. & Astrophys.

Keywords: 11.19.1 Galaxies:Seyfert 11.01.2 Galaxies:active 11.09.1 NGC 4151

For figures send postal address or FAX number to jdr@leicester.ac.uk

Abstract

We estimate the properties of clouds that form as a result of the interaction of the surface of a disc embedded in a supersonic outflow and heated by external irradiation. We find two regions where short-lived clouds are injected into the outflow and accelerated by ram pressure. We identify these with a broad line region and an intermediate line region. We compute the line strengths and profiles from a model of the cloud dynamics and compare the results with the observations of the nearest Seyfert galaxy NGC 4151, which, in its various luminosity states, has provided a large amount of emission line data. We show that the model parameters for this galaxy are constrained by just the CIV λ1549 line profile in the high luminosity state of the nucleus. We review briefly some of the data on broad line ratios, profiles, profile variations and transfer functions and show how much (if not all) of this data can be accounted for in the model. We also indicate how the X-ray data can be fitted into this picture.

1 Introduction

We can distinguish various approaches to understanding the broad emission lines from active galactic nuclei. In phenomenological models we attempt to obtain a distribution of photoionised gas that will reproduce the main features of the line ratios and profiles without regard to the dynamics of the gas or its relation to the system as a whole. Early investigations resulted in the now universally accepted cloud picture, but were ambiguous with regard to the cloud kinematics. More recent investigations of time lags between continuum and line variations restrict the scale of the cloud distribution and point to complex kinematics and a stratification in cloud properties with radial distance from the ionising source. To accomodate these observations, phenomenological models must incorporate a range of parameters or arbitrary functions (for example, Robinson 1995). An alternative approach is to try to model the cloud system dynamically. Gravity, magnetic fields, ram pressure and radiation pressure have all been considered

for the acceleration of pre-existing clouds (Carroll & Kwan 1985, Emmering et al. 1991, Capriotti, Foltz & Byard 1979, Shields 1978, Blumenthal & Mathews 1975, Mathews 1993). Two phase equilibria and shocks have been considered for the formation process (Mathews & Doane 1990, Perry & Dyson 1985). Models of this sort have been used to address either individual galaxies or classes of galaxies (Collin-Souffrin et al. 1988, Terlevich 1994).

The present paper stems from a phenomenological model (Cassidy & Raine, 1993) in which clouds are supposed to be injected from the surface of an accretion disc into a supercritical, mildly relativistic, outflowing spherical wind where they are accelerated and destroyed. Although the existence of such a wind is an assumption for the formation of which there is no firm theoretical evidence, we showed that this picture gives a good account of the large variety of line profile shapes that occur in active nuclei and we were able to relate characteristic features of the profile types to aspects of the physical model. This work was in turn based on a theoretical model (Smith & Raine 1984) of the formation and acceleration processes in a thermally driven wind from the disc surface which we now know to be untenable for the broad lines (Sect. 2). Here we present a new physical picture of the interaction of an accretion disc in an ambient wind in which the broad line clouds are formed as a result of Kelvin-Helmholtz instabilities at the interface. A further new feature of the model is that the thermally driven outflow from the disc provides a region of line emitting clouds (the intermediate line region, ILR) with properties intermediate between the true broad line region (BLR) and the narrow line region (NLR). The theory supports the phenomenology described in Cassidy and Raine. It enables us to go some way towards a detailed description of the broad line emission from NGC 4151, one of the most enigmatic (and hence theoretically challenging) of galaxies. In Fig.1 we give a schematic diagram of the main features of the model.

The picture we present attempts to address seriously from a theoretical viewpoint the wealth of detailed observational data that point to a complex, stratified, emission line region. Our model is similar to Emmering et al. (1991) except that they take magnetic forces to be partly responsible for the injection and acceleration of cloud material from the surface of the disc into the broad line region. It differs from biconical models (Zheng, Binette & Sulentic 1990) in that our cloud outflow fills a conical shell rather than the interior of a (double) cone and our cloud motion inherits an azimuthal component from the disc. Conversely, we differ from pure disc models (e.g. Shields 1978) since in our case there is a radial component to the cloud velocity. In contrast to the two component model of Collin-Souffrin et al (1988), we obtain also the low ionisation lines from the cloud component and not from disc emission. The two component model is certainly not applicable to NGC 4151 in any obvious way since in this source the CIV $\lambda 1549$ and MgII $\lambda 2798$ line profiles are similar to each other and both different from CIII] $\lambda 1909$.

Clearly our picture is not spherically symmetric so differs from, for example, Dyson and Perry (1985), Mathews (1993), Terlevich et al (1994) and many

others. Note that we do inject short-lived clouds into an outflowing wind but (in contrast to, for example, Dyson and Perry) the cloud material does not originate in the wind. Nevertheless, we agree with many authors in taking the components of the active nucleus to be a disc, a nuclear source of both radiation and particle flux and stars. We differ in that we explore the interaction of the nuclear wind and the disc as the source of emission line clouds. Of course, our nuclear wind must interact with the stars in the BLR as in the Dyson and Perry picture; but we assume that, for NGC 4151 at least, cloud formation from shocks induced in the wind by the present population of supernova remnants is too small to make a significant contribution to the BLR (although it may make some contribution to the ILR). We also neglect the contribution from bloated stars (Alexander & Netzer, 1994) and the stellar ionising continuum.

NGC 4151 exhibits changes of state that can be described as a sequence of intermediate Seyfert types. Ulrich et al. (1991) distinguish between a high luminosity state ($f_{\lambda 1455} > 15 \times 10^{-14}$ erg cm^{-2} s^{-1} Å^{-1}) and a low luminosity state ($f_{\lambda 1455} < 3 \times 10^{-14}$ erg cm^{-2} s^{-1} Å^{-1}). At its highest luminosity NGC 4151 shows features characteristic of Seyfert I nuclei with broad optical and UV lines (up to 30 000 km s^{-1} FWZI) and a high Hβ/[OIII] ratio (Clavel et al. 1990). At its lowest luminosity the broad lines have all but disappeared and the nucleus is described as a Seyfert 1.9. Changes between states take place on a time scale of weeks to months, short even in comparison with other such intermediate Seyferts. However, the extreme luminosities occur very rarely. In section 3 we shall show that the CIV line profile in the high luminosity state fixes the parameters of the model. We consider also the likely effect of reductions of luminosity using the theory of section 2 as a guide. In section 4 we explore the extent to which the model might yield agreement with the extensive range of observational data on this galaxy.

2 The Theoretical Basis

2.1 Introduction

In this section we shall show that for an accretion disc embedded in a supersonic outflow, and illuminated by an external radiation field, there are two regions from which clouds are injected from the disc surface into the ambient outflow. The inner of these regions yields clouds with the properties of the broad line gas (BLR) and the outer region can be identified with the intermediate emission line region (ILR). We shall anticipate this identification and refer to the two zones of the disc as the BLR and ILR. The theory will be developed in general and applied to the source NGC 4151; thus we shall write some numerical factors in equations in terms of the parameters for this galaxy, even though, of course, this will require us to assume the results of the fit to the observations in sections 3.

External illumination by X-rays raises the temperature of material at the surface of the disc to the Compton temperature. At sufficiently large radii this material is then hot enough to escape from the gravitational pull of the black hole (Begelman & McKee 1983). We have shown that if this material is subject to the ram pressure from a nuclear wind then unstable cooling leads to cloud formation (Smith & Raine 1984). Our original proposal that this is the mechanism for the formation of broad line clouds is, however, untenable. For a typical Compton temperature of the incident radiation field, $T_c = 10^7$, mass loss from the disc can occur only at radii greater than $r_c = 10^{19} m_8 / T_7$ cm for a black hole of mass $10^8 m_8 M_\odot$, where $T_7 = 10^7 T_c$ Even if the Compton temperature of the radiation incident on the disc differs from that in the line of sight to the observer (which is not the case in our model of NGC 4151) the inferred radius of the supposed BLR would still be larger than permitted by variability arguments. Furthermore, if the Compton temperature is 10^7K, the density in the clouds, at temperature 10^4K, will be of order 10^8 cm^{-3} (see equation (5)), too low to be compatible with the typical inferred value of the BLR ionisation parameter of $\log U \sim -2$. In addition, in order to obtain logarithmic line profiles in the line wings, we assumed that the clouds are long-lived. The longevity of the clouds is inconsistent with acceleration by a supersonic wind (since the clouds loose mass through the flanks on the order of a sound crossing time). Short-lived clouds in this model cannot produce acceptable line profiles (Cassidy, 1994) nor provide the variety of non-logarithmic profiles now observed in other sources (Robinson 1995). The requirements are relaxed somewhat if, as may be the case in NGC 4151, the Compton temperature is as high as 10^8K, but the overall conclusions are unaffected.

Nevertheless, this mass loss must occur, and, if the nuclear wind is present, cloud formation is a consequence. We shall show that these clouds must contribute to an intermediate line region. In the low luminosity states of NGC 4151 the ILR dominates the line emission; from this we shall deduce that these clouds may be sufficient to provide the main component of the ILR emission in this source.

We shall show further that within the Compton radius, r_c, the illuminated surface of the disc in the presence of the nuclear outflow is Kelvin-Helmholtz unstable. These instabilities, we argue, will grow and be entrained in the wind as BLR clouds.

In Cassidy & Raine (1993) we used a phenomenological picture based on the injection of clouds from the surface of the disc by an unspecified mechanism to generate the broad line region. This work gave a range of line profiles that could be matched to the variety of profile classes observed, but at the expense of a large number of adjustable parameters since the physical basis of the model was not specified. In the present paper we take a different approach: we construct a theory of the cloud injection process which enables us to relate some of the parameters of the system by self-consistency arguments. We then apply the results to one of the most difficult examples, NGC 4151, for which we can find

a set of values for the remaining parameters from a single observation of the CIV $\lambda 1549$ line profile at its peak luminosity. In particular we fix the angle of the disc to the line of sight. In a later paper we shall show that NGC 4151 (in each of its various luminosity states) can indeed be considered a typical active nucleus viewed from the particular line of sight, just over the top of the disc, at which the nearside of the flattened distribution of BLR clouds appears directly in front of the central continuum source.

Thus, to summarise, the active nucleus is supposed to contain a black hole, of mass m_8 in units of $10^8 M_\odot$; there is a disc, which is taken to be a source of material, but about which we make no assumptions other than that it is opaque with non-zero albedo; we require a central source of luminosity L_r, parameterised by $l_r = L_r/L_E$, where $L_E = 1.3 \times 10^{46} m_8$ is the Eddington limit luminosity; and we have a mass outflow which carries a flux of kinetic energy L_m. This matter flux, the Eddington luminosity and the disc inclination are the only true free parameters in the theory, apart, that is, from dimensionless parameters of order unity, behind which we hide our ignorance of some of the details of the physics. The results depend significantly on only one of these dimensionless parameters, the disc albedo. We also have to make assumptions about the continuum spectrum in those bands where it is not measured, but our results are not sensitive to this choice, except for some dependence on the Compton temperature of the disc illumination (which is not necessarily the same as the observed Compton temperature). As noted below, we prefer a Compton temperature of the illuminating radiation closer to 10^8 K than 10^7 K. The wind must be sufficiently optically thin to be compatible with the X-ray variability. We use the observations of NGC 4151 to calibrate this constraint. The interactions in this system then lead to a scattering of radiation in the wind on to the disc, a zone in which the disc surface is Kelvin-Helmholtz unstable, which is the BLR, and a zone in which the disc surface is the source of a thermally driven wind, which forms the ILR (Fig.1).

2.2 Wind Properties

The supersonic nuclear wind is taken to be spherical with a constant outflow velocity $v_w = 10^{10} v_{10}$ cm s^{-1} and to carry a power L_m in bulk motion. The wind density, n_w, is then given by

$$n_w = 4 \times 10^6 (L_m/L_E)(m_8/0.3) r_{16}^{-2} v_{10}^{-3}\ \mathrm{cm}^{-3}, \tag{1}$$

and the ram pressure is

$$P_m = 7 \times 10^2 (L_m/L_E)(m_8/0.3) r_{16}^{-2} v_{10}^{-1}\ \mathrm{erg\,cm}^{-3}. \tag{2}$$

The wind is fully ionized by the radiation field and heated to the Compton temperature out to a radius $r_{ad} = 3 \times 10^{17} l_r m_8 v_{10}^{-1}$ cm. Beyond this adiabatic cooling will start to become important but the wind temperature will not drop

substantially until $r = 10^3 r_{ad}$ (Smith and Raine 1985). The Mach number of the outflow is of order $100 v_{10} T_8^{-1/2}$ and the wind is typically hypersonic. The optical depth to electron scattering is

$$\tau_w = 2 \times 10^{-2} (m_8/0.3)(L_m/L_E) r_{16}^{-1} v_{10}^{-3}. \tag{3}$$

So, for NGC 4151, provided $L_m/L_E \leq 5$, we have $\tau_w \sim 1$ at $r = 10^{15}$ cm which is consistent with large scale X-ray variability on times of order 10^5 s. (Yaqoob et al. 1991, 1992). Then, consistently, $v_w = 10^{10}$ cm s$^{-1} \gg v_{esc}$ at 10^{15} cm (since $v_{esc} = 10^{10}((m_8/0.3)/r_{14})^{\frac{1}{2}}$ cm s^{-1}). We cannot reduce the outflow velocity significantly below $v_{10} = 1$ for a high value of L_m/L_E, as will be required to fit the high luminosity line profiles below. The nuclear outflow must therefore be mildly relativistic for consistency.

2.3 Properties of the disc

The radiation falling on the disc will significantly affect the surface if the energy falling on the disc is greater than that produced locally by viscosity in the disc. In particular the surface layers will be heated to the Compton temperature. Note that under these circumstances the disc may still have an optically thick, cool, geometrically thin core (Mobasher & Raine 1990) at this radius. Suppose the disc is illuminated directly (rather than by scattered radiation). Let the surface be given by $z = z(r)$. Then the luminosity intercepted by the disc between radii r and $r + \mathrm{d}r$ is proportional to $2\pi r \mathrm{d}z/r^2$. Let the flux falling on the disc be $(\phi L_r/4\pi r^2)\mathrm{d}z/\mathrm{d}r$ between radii r_1 (where $\tau_w = 1$) and r_{max}. (This defines ϕ.) Taking $z(r)$ to be given by a scale height in the hot surface layers of the disc when external illumination dominates gives $z(r) = \times 10^{15} T_8^{1/2} r_{16}^{3/2} (m_8/0.3)^{-1/2}$ cm. For the local dissipation in the disc it is reasonable to assume a steady state. But the irradiation from the central source may change on short time scales. In terms of a time-averaged luminosity parameter $\bar{l_r}$, we therefore have $L_r = 0.1(\bar{l_r}/l_r)\dot{M}c^2$ for an accretion efficiency of 0.1 and an accretion rate $\dot{M}$. This gives the radius at which external illumination equals the local rate of viscous energy generation as

$$r_{in} \sim 10^{16} (\frac{m_8}{0.3})^{2/3} (\frac{0.1}{\phi})^{2/3} T_8^{-1/3} (\frac{\bar{l}_r}{l_r})^{2/3} \text{ cm.} \tag{4}$$

This therefore gives an estimate of the inner radius of the BLR which consequently ranges between about 10^{16} cm and 5×10^{16} cm as l_r changes by a factor 10. The outer radius of the BLR depends on the flaring of the disc in the presence of the wind and is calculated in section (2.7) below.

The surface temperature of the disc is the Compton temperature. Beyond a radius $r_c = 3 \times 10^{17} (m_8/0.3) T_8^{-1}$ cm this exceeds the temperature at which material is gravitationally bound (Begelman et al 1983). The material escaping from the disc has been raised to a pressure $P = P_{rad}/\Xi'_{c,min}$ where Ξ is the

ionisation parameter $\Xi = P_{rad}/P_{gas}$ and $\Xi'_{c,min}$ is its value at which the gas can just remain in the hot phase. The escaping material therefore has a density $\rho = P/c_s^2$. Exposed to the ram pressure of the nuclear wind this material cools under constant pressure to 10^4K. Using $\Xi'_{c,min} = 3$ as a typical value for a Seyfert spectrum, the density of the clouds becomes

$$n_{ILR} = 10^8 \frac{(l_r/.1)(\phi/.1)T_8^2}{(r/r_c)^2(m_8/0.3)} \mathrm{cm}^{-3}. \tag{5}$$

These clouds constitute the ILR. Begelman et al. (1983) find that there is a fully developped disc wind extending from r_c to a radius $r_{iso} = 3(\bar{l}_r/0.1)T_8^{-1/2}r_c$ within which material is rapidly heated to T_c. Thus the ILR extends from within 3×10^{17} cm to beyond 10^{18} cm.

Most models of accretion discs are optically thick to the continuum in the BLR, but not usually in the ILR (Collin-Souffrin 1987, Mobasher & Raine 1990). Therefore the disc obscures any emitting material in the BLR on the far side from the observer, but not in the ILR. In the BLR we expect the albedo of the disc to be significant at least for resonance lines. Thus, we shall have to take account of reflection from the disc surface.

2.4 Disc-wind interaction in the BLR

Consider now the interaction between the disc and the nuclear wind in the BLR region. Suppose, contrary to our discussion above, that the disc surface were to remain cold and therefore essentially unexposed to the ram pressure of the wind. Then the pressure in the disc is balanced by the thermal pressure, $n_w kT_c$ in the wind. If a fraction ϕ of the radiation field falls on the disc, the ionization parameter (Begelman, McKee & Shields 1983) is therefore

$$\Xi = \frac{P_{rad}}{P_{gas}} = \frac{(\frac{\phi L}{4\pi r^2 c})}{(n_w kT_c)} = 2 \times 10^3 \frac{\phi L v_{10}^3}{L_m T_8} \tag{6}$$

for an inverse Compton temperature $T_c = 10^8 T_8$ K. By running the CLOUDY photoionisation code for an average quasar spectrum (Mathews and Ferland 1987), a power law with an energy index of -0.9, and a power law with the canonical slope of -0.7, we find that the material must be hot, with temperatures of 1.5×10^7, 1.0×10^8 and 1.6×10^8 at values of Ξ greater than of order 10^2, 10 and 1 respectively. The value of Ξ from equation (6) is therefore much greater than the maximum $\Xi'_{c,max}$ for the cold phase. Thus, contrary to our assumption (and in agreement with section (2.3)) the disc surface cannot remain cold. But, also, the disc surface cannot be hot and be exposed to the *full* ram pressure of the wind since in that case

$$\Xi = \frac{P_{rad}}{P_m} = (\frac{\phi L}{L_m})(\frac{v_w}{c}), \tag{7}$$

smaller than a critical value $\Xi_c = \Xi'_{h,min}$, the minimum for the hot phase. So, we can assume that the disc surface adjusts itself so that the disc is exposed to a pressure fP_m just insufficient to maintain the cold phase:

$$f = \phi l_r (\frac{L_E}{L_m})(\frac{v_w}{c})\frac{1}{\Xi_c}. \tag{8}$$

If, for example, $L_m/L_E \le 5$ and $l_r\phi = 0.01$, we have $f \ge 2\times 10^{-4}(3/\Xi_c)$.

From this we can deduce the density in the surface of the disc, n_d, since the disc pressure must balance fP_m at the Compton temperature. We obtain

$$\begin{aligned} n_d &= 10^{10} f(L_m/L_E) r_{16}^{-2} v_{10}^{-1} T_8^{-1} \text{ cm}^{-3} \\ &= 1.6\times 10^8 (\phi/0.1)(l_r/0.1)(m_8/0.3)\Xi_c^{-1} r_{16}^{-2} T_8^{-1} \text{ cm}^{-3} \end{aligned} \tag{9}$$

Next we show that this arrangement is Kelvin-Helmholtz unstable at the disc-wind interface. Rotation and infall of the disc material can be neglected since the rotational and infall speeds are small compared with the wind speed. Thus, for $n_d \gg n_w$ the instability operates on wavenumbers (Chandrasekhar 1961)

$$k > \frac{g n_d}{n_w v_w^2}, \tag{10}$$

where g is the gravity at the surface. Suppose the surface is at height $z = \zeta H$, where H is the pressure scale height at the temperature of the disc atmosphere, $10^8 T_8$ K. Then, the vertical component of the acceleration due to gravity is, approximately for $z \ll r$,

$$g = \frac{GM_{bh} z}{r^3} = 6.4(m_8/0.3) T_8^{\frac{1}{2}} r_{16}^{-\frac{3}{2}} \zeta \text{ cm s}^{-2}. \tag{11}$$

The height ζ is determined by pressure balance in the disc. For any disc model it is unlikely that $\zeta \gg 1$ (because the pressure falls off rapidly with height as exp(-ζ^2)), or $\ll 1$ (because the external pressure does not dominate the internal disc pressure). It is therefore sufficient to take $\zeta = 1$.

Using equation (9) for the density in the disc, we obtain

$$k > k_{min} = 2.6\times 10^{-16}(m_8/0.3)(L_E/L_m)(\phi/0.1)(l_r/0.1)\zeta v_{10} T_8^{-1/2} r_{16}^{-3/2} \Xi^{-1} \text{cm}^{-1}, \tag{12}$$

and potentially large columns

$$n\lambda_{KH}^{max} = 4\times 10^{26}(L_m/L_E)(m_8/0.3) r_{16}^{-1/2} v_{10}^{-1} T_8^{-1/2} \zeta^{-1} \text{ cm}^{-2}, \tag{13}$$

where

$$\lambda_{KH}^{max} = 2\pi/k_{min} = 2\times 10^{18}(0.01/\phi l_r)(0.3/m_8)(L_m/L_E)\Xi_c v_{10}^{-1} \zeta^{-1} r_{16}^{-3/2} T_8 \text{ cm} \tag{14}$$

is the length scale of the growing perturbations. Note that at the inner radius this is larger than the BLR, so this maximum, which is calculated assuming a uniform system, cannot be attained. The outer radius of the BLR will turn out to be of order 10^{17} cm, (section 2.7) so $\lambda_{KH}^{max}(r_{out}) \sim r_{out}$ i.e.the maximum scale of the growing mode is of the order of the size of the BLR. However, the growth time decreases for smaller wavelengths (and is infinite for the largest mode (equation (17)) so the disc surface will develop large rising rings of hot gas on various scales within the BLR. This gas is exposed to an increased pressure from the impact of the nuclear wind at which the material cannot remain hot.

The main contribution to cooling above about 10^6K is thermal bremsstrahlung, so the cooling timescale in the disc surface is

$$t_c \sim \frac{nkT}{10^{-27}n^2T^{1/2}} \sim 10^7(0.1/\phi)(0.1/l_r)(0.3/m_8)T_8^{3/2}\Xi_c r_{16}^2 \text{ sec.} \tag{15}$$

This is to be compared with the sound-crossing time, t_s. For material of column density, N_{col}, we have $t_s = N_{col}/nc_s$ and hence

$$t_s/t_c \sim (N_{col}/10^{23})T_8^{-1}, \tag{16}$$

independent of any parameters of the system. Thus, the hot bubble can cool coherently only in a relatively small column of density about 10^{23} cm^{-2}. Cooling to 10^4 K will tend to be one-dimensional producing a surface layer of this column density. The growth time of the instability is

$$t_g = (\frac{k^2 n_w v_w^2}{n_d})^{-\frac{1}{2}}(\frac{k_{min}}{k} - 1)^{-\frac{1}{2}}. \tag{17}$$

which, for scales $\lambda_{KH} \ll \lambda_{KH}^{max}$ depends only on column density so is unaffected by cooling. Perturbations on the cold surface grow on a timescale of order $10^{-4}t_s$. Thus, the surface will tend to ripple as it cools into clouds of number density, assuming cooling at constant pressure,

$$n_c = \frac{3 \times 10^{12}}{r_{16}^2}(\frac{\phi}{0.1})(\frac{l_r}{0.1})(\frac{1}{T_8\Xi_c}) \text{ cm}^{-3}. \tag{18}$$

Where the timescale for cloud formation, t_c, exceeds the variability timescale the factor of l_r in this equation should be replaced by its time averaged value $\bar{l_r}$. But for most, if not all, of the BLR we can ignore changes in cloud density. These clouds will be entrained into the nuclear wind.

We can now summarise how the instabilities develop. Hot rings grow on the disc surface and start to rise into the wind. The material at the surface of the rising bubble is exposed to a higher pressure and a shell of column of $N_c = 10^{23}$ cm^{-2} starts to cool towards 10^4K. The cool material is still Kelvin-Helmholtz unstable on scales less than N_c so cooling does not suppress the growth but will tend to break the rings up into clouds.. Thus, the effect of the instability is to

inject a spray of clouds of column density 10^{23} cm^{-2} into the nuclear wind. Let $\lambda_c = N_c/n_d$, the thickness of the shell of disc material that cools in a sound crossing time. The efficiency with which the hot bubble is injected as cold clouds depends on the ratio λ_c/λ_{KH}, since this is the fraction of material in the bubble that cools to form the surface shell. Thus the number of clouds injected as a function of radius is:

$$\lambda_c/\lambda_{KH}^{max} = 3 \times 10^{-4}(L_E/L_m)(0.3/m_8)v_{10}T_8^{1/2}\zeta r_{16}^{1/2}. \tag{19}$$

The important point is that this increases with radius as $r^{1/2}$ thereby weighting the outer clouds.

The density of the cold material at 10^4K is a factor $10^4 T_8$ greater than the surface density of the hot disc (equation (18)). Such densities (of order 3×10^{12} cm^{-3} for the innermost clouds in NGC 4151, falling to 3×10^{10} cm^{-3} in the outer BLR) are much higher than usually attributed to the BLR. We shall find such densities to be precisely those required for agreement with the CIV/CIII] line ratios and profiles.

2.5 Cloud injection

We argue next that these cool regions are injected into the nuclear wind with some velocity v_i and accelerated to some velocity v_c. Consider an elevated region of surface wave. The growing protuberance provides an obstacle around which the wind must flow. While the face of the perturbation is exposed to some fraction of the ram pressure, the top surface will be subject to a smaller pressure closer to the thermal pressure, P_w, in the wind. Since the disc material is on average at $fP_m \gg P_w$ the incipient hot bubble, area A, is accelerated upwards to a velocity v_i given by

$$fP_m A = (A\lambda_{KH} n_d m_p)(\frac{v_i^2}{\lambda_{KH}}). \tag{20}$$

This gives $v_i^2 = P_d/m_p n_d$ or $v_i = c_d$, the sound speed in the hot disc surface. The sprays of cold bubbles are injected with velocities normal to the disc of order $10^8 T_8$ cm s^{-1}. Note that, even if the Compton temperature of the disc surface is of order of the observed average of 10^7K, mechanical heating of the atmosphere may raise the temperature above $T_8 \sim .1$ so injection velocities above 3×10^7 cm s^{-1} may be possible (King & Czerny 1989). (In fact we shall take $T_8 \sim 1$ for NGC 4151 on other grounds; see sect.3) The clouds will also inherit a rotational velocity from the disc. The disc surface must flare to a scale height at the Compton temperature at the outer edge of the BLR (ie $H/r \sim 0.5$) so the rotational velocity will not be Keplerian. However, since $H/r < 1$ throughout the BLR and $H/r < 0.1$ for much of the region, we shall take the azimuthal component of the cloud velocity to be Keplerian on injection. In fact, the drag on the cloud as it moves across the radially flowing wind reduces

the rotational component v_ϕ significantly in a time $(c_s/v_\phi)t_s$, where t_s is here the sound crossing time in the cloud. Since the azimuthal velocity in the disc is supersonic, the rotational component is strongly attenuated. So although it cannot be neglected in forming the line profiles (since it is largest in the initial part of their motion where the clouds spend the most time) departures from Kepler velocities are unlikely to be of crucial significance. We therefore assume the clouds inherit a Keplerian velocity from the disc on injection. The injected clouds will be subject to the full ram pressure of the wind. This will act to compress and accelerate the clouds but also to destroy them. We expect the cloud survival time to be of order a sound crossing time in the uncompressed cloud. Thus, approximately, for the cloud acceleration, we have (ignoring mass loss)

$$\rho_c A \lambda_c \frac{dv}{dt} = \rho_w v_w^2 A \tag{21}$$

or, taking $t = t_s = \lambda_c/c_s$ (c_s is the sound speed in the cold cloud),

$$v_c = c_s(\frac{v_w^2}{c_s^2})(\frac{\rho_w}{\rho_c}) = f^{-1}c_s, \tag{22}$$

or

$$v_c = 3\times 10^8 \frac{\Xi_c}{(\phi/.1)(l_r/.1)v_{10}}(\frac{L_m}{L_E})\ \mathrm{cm}^{-1} \tag{23}$$

using equation (8). For $f \sim 5\times 10^{-4}$ we obtain speeds up to 2×10^9 cm s^{-1}. However, on the one hand, this estimate takes no account of mass loss from the clouds over their lifetime, whereas in the numerical computation of the cloud trajectories this is incorporated through a simple model of cloud disruption (see sect. 2.6). This estimate, of the cloud velocities should, as a result, be increased by a factor of, approximately, the ratio of the initial and final column densities of the cloud, $(N(0)/N(t_s))$. On the other hand, the numerical computation takes account of gravity and the full three dimensional geometry with the overall result that the maximum final velocity (hence the line half-width at zero intensity) is of order 10^9 cm s^{-1}.

Notice that, other things being equal, the cloud velocity (equation (23)) appears to increase as the luminosity in the radiation field, l_r, goes down. This is the converse of what is observed for NGC 4151. However, we do not expect the power in the wind to be independent of that in the radiation field. To produce the observed reduction in line width at low luminosity exactly in this theory we must require that the momentum flux in the wind, L_m/v_{10}, be proportional to L_r^q with $q\sim 2$. This would be the case, for example, for a pair driven wind. We obtain qualitative agreement provided P_m decreases with L.

2.6 Cloud destruction

Since the clouds are accelerated in a supersonic wind they are subject to disruption by mass loss through the flanks, where the wind pressure is reduced

relative to the cloud face as the wind material accelerates round the cloud. The results are not too sensitive to the manner in which the clouds break up, provided that the result of evolution is to reduce the column density, so we take a simple model. We choose for the mass of the cloud $M(t) = M(0)(1 + t/t_s)^{-2}$ where t_s is the sound crossing time in the cloud. Thus, approximately 90% of the cloud is lost in two sound-crossing times. The area of the cloud facing into the wind and the matter density in the cloud are assumed to be constant while the column density decreases with the mass.

We can give some justification for this model as follows. Mass flow through the flanks of a cloud at the sound speed leads, after a time t, to an increase in area facing the source to $\pi r^2 = \pi r_0^2(1 + c_s t/r_0)^2$, where r_0 is the initial radius of the face of the cloud. This escaping material will be heated to the Compton temperature and entrained in the wind. It is therefore lost from the cloud. Thus the mass of the cloud is reduced by a factor $(1 + t/t_s)^2$ while the area of cold cloud material remains constant. Mass must flow through the cloud to supply the mass loss. Assume that the density in the cloud remains constant. (This would be a reasonable approximation for a flattened cloud evolving in pressure equilibrium, which is probably not too far from being the case.) Consequently the column too decreases by this same factor.

2.7 Outer limit of the BLR

There is an outer limit to the cloud injection region set by the extent to which the disc surface flares to intercept the momentum flux in the wind. The disc pressure must be provided by new wind material further from the disc midplane as r increases, because the cloud acceleration at smaller r extracts momentum from the wind close to the disc surface. At the outer edge of the BLR clouds rise to a height

$$z_{out} \sim t_s v_i \sim 10^{19} \frac{T_8 \Xi r_{16}^2}{(\phi/.1)(l_r/.1)} \text{ cm} \gg H(r_{out}). \tag{24}$$

The momentum flux in the wind in a wedge of azimuthal extent $\Delta\phi$ and altitude $\Delta\theta = z_{out}/r_{out}$ is, approximately

$$\Delta\phi \int_0^{\Delta\theta} sin\theta d\theta \, v_w^2 cos\theta \rho_w r^2 \sim 10^{36} \frac{r_{16}(L_m/L_E)T_8\Xi_c}{(\phi/.1)(l_r/.1)} \Delta\phi. \tag{25}$$

The maximum momentum flux in the clouds is

$$\Delta\phi \dot{M}_{max} v_c = 2 \times 10^{36} \log r_{16} [\frac{(l_r/.1)(L_m/L_E)}{(\phi/.1)T_8\Xi_c v_{10}}]^{1/2}. \tag{26}$$

We obtain equality when $r_{16} \sim 10$. Thus, for the maximum cloud injection rate, the outer radius of the BLR in NGC 4151 is at 10^{17} cm.

We have seen that the disc must flare to a scale height at the Compton temperature at the outer limit of the BLR. For NGC 4151 ($m_8 = 0.3$) the scale height is $H = 1.5 \times 10^{15} T_8^{\frac{1}{2}} r_{16}^{\frac{3}{2}}$ or 4.5×10^{16} cm at $r_{out} = 10^{17}$cm if $T_8 = 1$. So the disc flares to about .45 radians or about 30^o across the BLR. Beyond the BLR is a region in which the hot disc atmosphere rises with $z \sim H \propto r^{3/2}$ until this material escapes in a wind beyond 3×10^{17} cm.

2.8 The ILR

The mass flow into the ILR from the thermally driven disc wind can be estimated by assuming the heated material flows out at the sound speed; thus

$$\mathrm{d}\dot{M} = n_d c_s m_p (2\pi r \mathrm{d}r). \tag{27}$$

The density in the disc surface n_d is $10^{-4} n_{ILR}$ (equation (5))and $c_s = 10^8 T_8^{1/2}$ cm s^{-1}. Assuming, as shown in Smith and Raine (1982), that the material cools into clouds of column density $\sim 10^{23} T_8$ cm^{-3}, we obtain for the sound crossing time in a cloud, t_s,

$$t_s = 10^9 (r/r_c)^2 (m_8/0.3)(0.1/l_r)(0.1/\phi) T_8^{-1} \text{ s.} \tag{28}$$

If the clouds survive for of the order of a sound crossing time only, we obtain

$$dM = t_s d\dot{M} = 2\pi 10^{-3} T_8^{3/2} r \mathrm{d}r, \tag{29}$$

and hence, for the mass in clouds in the ILR,

$$M_{ILR} = 3(l_r/0.1)^2 (m_8/0.3)^2 T_8^{-3/2} M_\odot \tag{30}$$

between the inner and outer radii given in section (2.3). We shall show this is sufficient to provide the constant narrow component of the BLR emission. For reference, the covering factor of the clouds (assumed spherical), is of order $.01 T_8^{1/2} \log(3(l_r/0.1) T_8^{-1/2})$ and the number of clouds is about $10^3 (l_r \phi/0.01)^2 T_8^{1/2}$. These estimates all lower limits since they assume the clouds survive only a sound crossing time.

3 The model profiles

The key to the comparison of our model with observations is the fit to the high state profile of the CIV line. In our earlier paper (Cassidy and Raine, 1993) we presented such a profile fit as an example of a Df class profile. This is reproduced in Fig. 2 here.

The requirement of sufficient cloud acceleration fixes L_m/L_E (equation (23)). We need $L_m/L_E \sim 5$, an unexpectedly high value, since it implies that, in the

high state, most of the energy output from the central source is in the nuclear wind. If we require $L_m/v_{10} \propto l_r^2$ (section 2.5) then $L_m/L_E \ll 1$ in the low state and there is no overall problem in hiding the wind energy. The profile fit, given the column density, fixes the inner radius at $r_{in} = 10^{16}$cm and hence $m_8 \sim 0.3$ (equation (4)). This, of course, gives us L_E and hence $l_r = L/L_E$ from observational estimates of the bolometric luminosity, L. We use $L/L_X = 10$ to estimate L from the X-ray luminosity L_X (sect. 4.2) giving l_r in the range .1 to .01. In fact, with the radial extent of the BLR *fixed*, rather than allowed to vary according to equation (4), order of magnitude changes in l_r affect the line profile of CIV only through small changes in the core. Our chosen range of l_r does, however, allow a close match to the line ratios (sect. 4.3) and is consistent with our estimate of the numerical factor in equation (4). Finally, the injection velocity v_i is fixed by the separation between the blue peak and the central peak.

Fig. 2 corresponds to the following choice of parameters: black hole mass $m_8 = 0.3$, corresponding to $l_r(max) = 0.1$; flux of energy in the nuclear wind $L_m/L_E = 5$; normal component of the cloud injection velocity $v_i = 2 \times 10^8$ cm s^{-1}. In addition, only clouds with column densities corresponding to 10^{23} cm^{-3} at the inner radius are considered.

The continuum has been taken as the Mathews and Ferland spectrum for this figure, although a power law gives essentially the same result. The cloud injection velocity is consistent with a Compton temperature rather higher than that for a Mathews and Ferland spectrum, but might be appropriate for a power law with no EUV excess (Sect. 1). In any case much of the radiation incident on the disc surface will be that emerging from the backs of the clouds forming close to the surface and will consequently be in the form of hard X-rays with a raised Compton temperature. We therefore believe the required high injection velocity to be reasonable.

In our previous work the fit to the CIV line was made with the inner and outer radii of the BLR, the cloud density and the disc flaring chosen freely. These are now, in principle, derived quantities. We have allowed small factors between the order of magnitude estimates of these quantities we have made for the model in section 2 and the values chosen for the figure. We have used $r_{in} = 1.4 \times 10^{16}$ cm and $r_{out} = 1.0 \times 10^{17}$ cm for the inner and outer radii of the BLR, respectively, and $n = 3.6 \times 10^{12}$ cm^{-3} for the density at r_{in}. The disc flares by 30^o (sect. 2.7).

The best fit for the line of sight, given the parameter values above, is 58^o to the disc normal. This fit we have judged by eye: it can be seen from figure 2 that the smooth model curve cannot fit the small scale detail of the profile, a problem which is apparent in the χ^2-values. In judging our claim that the model does fit this observation one should bear in mind the difficulties that all models have in reproducing even the broad features of the profiles for this particular galaxy. We should not expect the sort of fine detail in figure 2 to emerge here; we might expect it to be associated with the fact that clouds are injected into

the wind in bunches.

Our line of sight passes close to the disc surface as required if the clouds are to partially cover the X-ray source. In addition, the light curves are most simply explained if there is emitting cloud material in the line of sight. The absence of a UV bump in this galaxy might be accounted for by sufficiently anisotropic emission of the UV, although it is difficult to see how this might be achieved physically.

Note that the double peakiness of the computed line in Fig 2 is a result of a complex emission profile, and does not involve absorption. However the dip between the peaks is shallower in the model than in the observed line and almost absent if the disc albedo is non-zero (Fig 2b). This suggests that *some* true absorption must be involved in this feature. Such absorption may arise if the inner CIV emitting clouds are obscured by clouds further out. This is possible in NGC 4151 because of the special angle to the line of sight. The variability in the depth and position of the absorption is also in principle compatible with this picture. The details do not affect the parameter values we obtain from the profile fitting and will be discussed elsewhere. We conclude that the observed CIV line profile constrains the model parameters quite tightly and that the predicted values of derived quantities provide significant tests of the self-consistency of the model.

The disc itself is assumed to obscure either partially or totally the line emission from clouds on the bottom side. (In section 4.6 we shall argue in favour of total obscuration and a non-zero albedo, but we need to investigate the properties of the partially obscured model to do this.) Without any obscuration of clouds below the disc the line would be triple-peaked. In the case of partial obscuration the line emission from each cloud is assumed to be blocked wherever there is material moving in the disc along the line of sight with a relative velocity that is within a thermal width of the line centre. What appears as the red peak in the observed line is therefore the central peak of the unobscured profile. This will be relevant to the behaviour of the two peaks when we consider variability in section 4. Finally, in section 4 we shall be led to consider a component reflected from the disc surface. In figure 2 we show the fit for both a partially obscuring disc with an albedo of zero and for a totally obscuring disc with an albedo of 0.3. (In the latter case the disc is, of course, taken to be optically thick out to large radii, so the optically thin and partially obscuring regions in Fig. 1 are absent.)

4 Comparison With Observations

Detailed studies of NGC 4151 have been prosecuted now for about 25 years. We attempt to summarise here what appear to be the main results of these observations. Given the determination of the model parameters by the observations presented so far, we consider how the remaining data might be interpreted.

4.1 Luminosity States

The profile fitting of CIV fixes the inner radius of the BLR (hence the black hole mass) and the properties of the wind. In intermediate luminosity states the narrower CIV and MgII profiles are obtained by changes in the wind parameters associated with decreased luminosity (Sect. 4.2). At low states most of the BLR must disappear. This could be attributed to obscuration of the inner clouds or to the suppression of cloud formation in the BLR. Obscuration would have to be restricted to the clouds (and not affect the central continuum source) since there is no correlation with, for example, X-ray absorption features. It might therefore refer to an obscuring disc; in any case it would require a special line of sight, not only for NGC 4151 but presumably also for all similar intermediate Seyferts and for radio galaxies that lose their broad lines intermittently (for example, 3C390.3). In NGC 5548 there was no evidence for obscuring material in X-rays when the broad lines disappeared (Loska et al. 1993). We therefore propose to associate the low state with a lack of inner region clouds. A unique feature of the model is the short timescales over which the inner clouds are removed once injection is stopped (of order a cloud sound crossing time, $3\times10^4 r_{16}^2$ s). Thus, the time lag for the change between intermediate Seyfert types following a transition in the luminosity state is by the light-crossing time of the inner part of the BLR, not by structural changes in the BLR or of some outer obscuring regions.

4.2 Line Widths

In its relatively infrequent highest luminosity state the relative widths of the CIV, MgII and CIII] lines are exceptional amongst AGN. At their broadest the FWHM for CIV and Mg II are between 4000 and 6000 km s^{-1}. The corresponding FWZI are 30 000 and 20 000 km s^{-1}. Unusually for AGN, CIII] λ1909 is much narrower with a FWHM of 1600 km s^{-1} and FWZI of 3500 km s^{-1} (Clavel et al 1990). This arises from the high density of the inner BLR clouds ($> 10^{10}$cm^{-3}) which supresses the CIII]λ1909/CIVλ1549 ratio. Sometimes MgII shows the characteristic double peak of CIV and sometimes the blue peak is either absent or very weak (Ulrich et al. 1984, 1991). In the low state the CIV and MgII lines are much narrower, around 4000 km s^{-1} HWZI, with suggestions of a broad base, while CIII] is unchanged. Thus, in the low state, all three lines have similar profiles.

The model fit to the profiles requires both a small radial extent for the BLR and high density clouds. This results in the similarity of MgII and CIV line widths (FWHM) while CIII] is much narrower. Although this is not shown, MgII is somewhat narrower than CIV, as required, with the difference diminishing at lower luminosity.

However, MgII does not always show the characteristic double peak of the CIV line. Sometimes the blue peak is either absent or very weak (Ulrich et al.

1991). We can obtain such behaviour by supressing the MgII emission from clouds immediately leaving the disc which also gives a narrower line profile in agreement with Ulrich et al. However, such behaviour does not appear to arise naturally in the model.

In Fig. 3 we show the effect of changing the obscuration properties of the disc compared with the CIV line profile observations on Mar 21 and Mar 25 1991 from Ulrich et al. (1991). We allow the disc to become completely opaque at less than 1×10^{16} cm and at less than 5×10^{16} cm respectively, so emission from the cloud distribution on the far side of the disc is more completely removed. Equivalently, we may regard these figures as showing the effect of a changing albedo for a completely obscuring disc. We have not been able to mimic these changes by any other combinations of alternative parameters or as variability effects (which would be included as a radial dependence in the cloud illumination). The change on the red side of the blue peak (with little or no change on the blue side) is a signature of a flared disc, the inner clouds initially moving inwards as they leave the disc.

We show the effect on the CIV line of a reduction in the efficiency of cloud acceleration in fig. 4. The width of the line is reduced, although this reduction is limited by the rotational and injection components of the cloud motions. Penston et al. (1981) show a sequence of CIV profiles between Feb 1978 and Jan 1979 as the continuum varied from the high to intermediate state. The most prominent feature is the disappearance of the profile wings. We would therefore like to associate the reduction in cloud acceleration with the decrease in luminosity. This cannot be the direct effect of radiation pressure acting on the clouds which cannot accelerate clouds to more than the internal sound speed over a sound crossing time. Since the survival time of the inner clouds (of order 10^5s) is less than the 10^6s it takes for the nuclear wind to reach the BLR it is possible for a reduction in the wind power to influence the cloud velocities in the wings of the lines. Since the cloud velocity depends on L_m/Lv_w) (equation (23)) the line width will decrease with L if the flux of momentum in the wind decreases with L more strongly than direct proportionality. If $L_m/v_w \propto L^2$ then fig. 3 represents the effect of an order of magnitude change in luminosity after the effect of a reduction in wind power has had time to propagate through the BLR..

Further reduction of the cloud acceleration has no effect on the profile widths since the rotational velocity now dominates. The resulting profiles are too wide to represent the low state observations. However, as the luminosity drops the inner radius of the BLR will move out (equation (4)). We obtain the further reduction in the profile width required in the low state if we simply suppress the cloud formation within a radius of about 6.5×10^{16} cm, consistent with our estimate for $l_r = 0.01$ of 5×10^{16}cm. This is in agreement with Peterson (1988) and Ulrich (1986) who show that in the lowest state virtually all of the line emission arises from outside the high density region in the BLR. The remaining BLR clouds provide a line of the observed FWHM (Fahey et al. 1991). Even

so there is still a marked deficit in the core; in our model this missing flux must come from a distinct region. Fig. 5 shows the comparison with the data of Fahey et al. (1991). The width of this missing emission is similar to that of the CIII] line and the ratio of flux in the CIV core to that in the broad component of CIII] is normal for AGN!

Our profile for CIII] from the BLR, normalised to the same peak intensity, would be similar to CIV, in complete contradiction to that observed. However, the high inner cloud density means that the flux in this component of the CIII] line is merely 10 per cent of the observed flux. The remaining flux consists of 70 per cent from the NLR (Ulrich et al. 1984) leaving a missing 20 per cent which we attribute to the ILR. The computed BLR profile then forms a shallow broad base to the observed line.

These observations clearly suggest that the bulk of the CIII] is coming from a separate region in which the CIV/CIII] ratio is typical. This is the intermediate line region (called BLR3 in Ulrich et al. 1986). It is interesting to note that the ILR is a prediction of the model resulting from just the fit to the profile of CIV in the high and low states. We get additional confirmation of this from another set of low state profiles (Ulrich et al. 1984) in which the BLR contribution is almost entirely absent and the CIV, MgII and CIII] profiles are very similar. We can show that the thermal disc wind gives rise to sufficient material to account for the CIII] emission. The flux in CIV is of order 10^{11} erg cm^{-2} s^{-1} which translates (see Table) to a luminosity in Hβ of order $10^7 L_\odot$ at 20Mpc. (We have not found a directly measured value for the Hβ flux.) Since CIII]/H$\beta \sim 3$ whereas photoionisation models of the ILR type clouds typically give CIII]:H$\beta \sim 1$, about 1/3 of the Hβ flux must be from the ILR. From standard recombination theory we can estimate the mass in the ILR as $30 \times M_\odot (L(H\beta)/10^9 L_\odot)(10^9 \mathrm{cm}^{-3}/n_e)$. The average density is in the range 10^8 cm^{-3} to 3×10^7 cm^{-3} between r_c and $3r_c$(equation (5)). Thus the mass required to provide all the CIII] emission is between 1-10 $M_\odot$. This is close to our estimate of the mass available (equation (30)). Thus the disc wind can provide sufficient material to account for the CIII] emission from the ILR, although we cannot rule out some contribution from other sources. Furthermore the existence of the ILR is reinforced by variability observations: Ulrich et al. (1984) found that CIII] does not vary on a time scale of less than a year. Snijders (1990) has detected an underlying weak broad variable component which could be attributed to the BLR. This implies that the BLR, as proposed here, and the ILR cannot merge but that there is a gap between the outer the BLR and the inner ILR.

It is important to note that NGC 4151 is far from unique in possessing an ILR. IUE spectra of 3C 390.3 between 1978 and 1986 (Clavel and Wamsteker 1987) show changes between broad high state BLR profiles and narrow low state profiles which we can attribute almost entirely to an ILR. Yee and Oke (1981) compared the luminosity of the nuclear component with that in the Balmer lines for 3C 390.3 and 3C 382 and found that the permitted line flux departs

significantly from a direct proportional dependence on the nuclear continuum. For both objects the 1980 scans show a different behaviour from those of earlier epochs. Firstly, both objects showed marked changes in the Balmer line profiles. Secondly, between 1979 and 1980 the Balmer line fluxes of each had changed significantly without an accompanying change in the continuum luminosity. (The same behaviour is exhibited by 3C 120 (Oke et al. 1980).) A simple time lag cannot explain completely the data for 3C 390.3 because it would produce much more scatter in the relation between the line flux and nuclear continuum. Therefore Yee and Oke suggested a two component BLR, one component reacting on a short timescale and the other on a long timescale. This second component is equivalent to our ILR.

Crenshaw, Peterson and Wagner (1988) found that the decomposition of profiles into broad and narrow components in 3C 445 leaves a residual component for Hβ and Hα. They claim that this component probably arises from a region kinematically distinct from the narrow [OIII] emitting region.

From the [OIII] profiles of Seyfert 1 galaxies van Groningen & de Bryun (1989) found that 10/12 objects possess broad wings implying densities in the region of 10^6 cm^{-3}. They call this a transition region intermediate between the BLR and NLR.

4.3 Line ratios

The average CIV λ1549 / CIII] λ1909 and CIVλ1549/MgIIλ2798 line ratios are much higher than is typical in AGN or quasars: Clavel et al. (1990) found ratios of 7.2 and 6.3 respectively. However, these values are highly variable and were found to correlate positively with the continuum flux. In the December 1989 outburst Clavel et al. found CIV/CIII] = 11.0 and CIV/MgII = 8.0. In the wings of the lines the ratios were even higher with CIV/CIII] > 50 and CIV/MgII $\simeq 10$. Similarly, Ulrich et al. (1991) find CIV/CIII] > 10 for $|v| > 2400$ km s^{-1} and CIV/CIII] > 20 for $|v| > 4000$ km s^{-1}, in this case independent of the value of $f_\lambda(1455\mathring{A})$. Nevertheless, in the line cores, the CIV/CIII] ratio is ~ 5, similar to values found in typical quasar spectra.

In table I we show the observed line ratios and the model predictions for two representative ionising continua. The Mathews and Ferland spectrum is an average over observed AGN. However, NGC 4151 is not an average object. In our picture this is simply a consequence of a rather special line of sight. But, even if the continuum emission from AGN is anisotropic, in NGC 4151 we see just that ionising spectrum incident on the BLR clouds (as modified by the presence of the clouds in our line of sight). It is possible therefore that the ionising continuum more closely resembles the unreprocessed power law with slope -0.9 (e.g. Nandra & Pounds 1994). To illustrate the difference this might make we have shown in table 1 the results from the model of a power law slope -1 for various luminosity states. (The slope in X-rays is only weakly dependent on luminosity (Yaqoob & Warwick 1991).) Also shown for comparison is the photoionisation model

calculation of Ferland and Mushotsky (1982) for a homogeneous BLR and an extrapolated spectrum corrected for X-ray absorption. It is interesting to note the improved agreement for MgII with the power law spectrum (although this conclusion is sensitive to any change in the column density).

In the high state the observed low CIII]/CIV ratio arises from the high density clouds in the BLR. At lower luminosities the contribution from the ILR is increasingly important and the ratios are predicted to become closer to typical values. The low state ratios do not appear to be given in the literature, but since the low state profiles involve the line cores where the high state ratios are more normal, we expect this prediction to be borne out.

Note that, as for other inhomogeneous models, there is no incompatibility between the ionization parameter deduced from line ratios and that deduced from reverberation maps of the size of the BLR. Note also that for the parameters of the model appropriate to NGC 4151 the clouds are found to move only a relatively small radial distance from their point of origin on the disc; the mean gas density in the clouds therefore follows fairly closely $n(r) \propto 1/r^2$. (This is not the case, in general, in systems where the normal injection speed is lower or where the BLR has a larger radial extent.)

4.4 Blue shifted 'absorption'

A double peak in the CIVλ1549 line was first noted by Anderson and Kraft (1969). Cromwell and Weyman (1970) and Ferland and Mushotzsky (1982) also report a *variable* feature on the blue side of the CIV line which they discuss in terms of variable absorption. Profiles showing this feature in a number of different luminosity states of NGC 4151 are presented by Penston et al. (1981), Ulrich et al. (1984) and Stoner & Ptak (1986). From these it is clear that the absorption feature varies, both in wavelength and relative depth in response to the variations in the continuum

In the model a double peak in the CIV line profile is the result of a contribution from rotational motion together with a blue shifted component from the injection velocity. The corresponding red shifted peak from clouds on the far side of the disc is obscured. The position of the trough in the profile moves towards lower velocity as the continuum luminosity decreases in agreement with observation. Nevertheless the depth of the trough in the model profile in the high luminosity state is significantly shallower than observed. It is likely therefore that some true absorption is also occuring in this velocity range, perhaps as a result of obscuration of the inner broad line clouds by those at larger radii. The overall absorption line structure is complex and we plan to return to the subject elsewhere.

4.5 Profile asymmetries

In 1986-88 all the broad lines were asymmetric with more flux in the red wings. The mid-points of the FWHMs were shifted blueward with respect to the narrow line centres by 1000 km s^{-1}. The narrow lines themselves show a small blue shift with respect to the galaxy. Ulrich et al. (1984) find for CIV that the HWZI in the blue exceeds that in the red. Yet the high luminosity profile published by Fahey et al. (1991) clearly shows excess emission and larger width in the red wing. For Mg II the red and blue wings have similar widths with more emission sometimes in the red. Note that the red wing in CIV may be blended with HeII $\lambda1640$ and OIII] $\lambda1663$ (Clavel et al. 1987); the MgII blue wing may be affected by He I $\lambda2733$ or the Fe II multiplets UV62 and 63. Large changes in the ratio of intensities in the wings between campaigns and different responses of the red and blue wings to continuum variations have been observed by Ulrich et al. (1991). With no reflection or obscuration from the disc the red and blue wings of the high state model profile are symmetric, but become red asymmetric with the inclusion of a non-zero albedo. Changes in the asymmetry are obtained in the model from changes in the disc albedo, since this affects mainly the intensity and lag of the red component. In the low state the model CIV (or MgII) profile is asymmetric towards the blue i.e. the blue wing is wider and has more flux (fig. 5). We need to resolve the problem of blending and to include non-steady state profiles in order to make a firm comparison with the observations.

Ulrich et al (1991) also note a transient red component in CIV possibly connected with the narrow so-called L_1 and L_2 components which are visible only in the lower luminosity states. The L_1 and L_2 features cannot come from our BLR. They may arise from gas associated with the linear radio structure. The intensities of L_1 and L_2 are not correlated with the continuum flux, but are well correlated one with the other. The features have a large velocity separation but any time delay between the variations has to be less than 4 days (Clavel et al. 1987). Thus a structure close to the plane of the sky is indicated. If this is the radio structure then it is consistent with our model.

4.6 Variability

Ulrich et al (1984) found typical 2-folding timescales for CIV of 19-47 days and for Mg II of 27-72 days; the shortest two-folding timescale over a period of about 2 years of observation was 7 days for CIV and 20 days for MgII. The light curves of CIV and Mg II are similar to that of the continuum (Clavel et al. 1990) with CIV undergoing changes greater than 60 per cent but MgII less than 50 per cent. However, the CIII] line remains constant. The transfer functions for MgII and CIV are similar and show zero delay. This is contrary to Clavel et al. (1990) who observed a delay of 4 $\pm$3 days, but any discrepancies can be explained by varying continuum pulse lengths.

The peak of the line response to a continuum pulse gives a characteristic

lag time. For NGC 4151 there is effectively zero delay in the *initial* response of the line as a result of the presence of material in the line of sight. For a short continuum pulse the *peak* occurs near zero delay because there is a significant fraction of the clouds within a sampling interval of the line of sight. In its low state, where the inner BLR clouds are absent, clouds in the line of sight still give an immediate response, but the *peak* response now occurs between 10-20 days, corresponding to the time at which the equal delay surfaces contain the maximum number of clouds.

For a non-spherical BLR, such as we have in the model, this lag depends on the length of the continuum pulse as well as the BLR geometry. For a short continuum pulse, duration less than or equal to the sampling time, the inner clouds dominate the transfer function so the peak occurs at small time delay. For longer pulses the delay is determined by the peak of the emission reponse at larger radii. Such a dependence has been confirmed for NGC 5548 by Netzer (1991).

In Fig. 6 we show the model response of the CIV line to a delta continuum pulse from zero background for a partially obscuring disc with zero albedo. The lag is $\sim 1/2$ day. Mg II and the contribution of the BLR to Hβ are predicted to respond similarly. The sampling time in the only available observations of the transfer function of NGC 4151 (Netzer 1991) is ~ 3 days. Within this resolution the line response of CIV is indeed immediate. In the model response there is a second peak which is the signature of the Keplerian motion of the clouds; there is no evidence for this in the observed data, but the resolution is almost certainly too low.

If we consider the transfer functions for the line wings and core separately we find that changes to the bulk of the core lag those in the wings and that, for the partially obscuring disc, the blue wing leads the red. The former agrees with observation; the latter does not. The 2D transfer function is difficult to construct observationally and none appears to be available for NGC 4151. Fig. 7 shows our prediction for the 2D transfer function for CIV with the same conditions as in Fig. 6 and with zero albedo for the disc. It is again clear that changes in the blue wing lead those in the red in probable disagreement with observation.

We remedy this discrepancy by taking a non-zero disc albedo. The transfer function for this reflected component is shown in fig. 8 for a reflection efficiency of 0.3. It can be seen that incorporating reflection will give a transfer function in which the red and blue components of the line respond with the same lag to continuum changes.

4.7 Profile variations

Gaskell (1988) found that variations in the red wings lead the blue in CIV and Mg II by a few days. The precedence of the red wing is not confirmed by other observers. As Gaskell points out, the exclusion of the *low state* of April 21 1980

in the cross-correlation function changes his result. Clavel et al. (1990) found equal delays in the red and blue wings of 3.2±3 days. This is consistent with Ulrich et al. (1991) who find delays in the response of the wings less than their sampling time of 5 days, although the red and the blue wings do not always respond to continuum changes in the same way. Fahey et al. (1991) found that the blue peak of the CIV line exhibits stronger variability than the red peak. The emission of the red peak is also strongly correlated with the total CIV flux, whereas the blue peak seems to be more sensitive to variations in the CIV flux and exhibits a sharp turn-on near $f_{CIV} = 10^{-11}$ erg cm^{-2} s^{-1}.

Clavel et al. (1990) observed a fractional variation in the flux in the CIV wings ($|v| \geq 3000$ km s^{-1}) of 0.34, much larger than that of the line core ($|v| <3000$ km s^{-1}), of 0.12. The same pattern is observed in the MgII lines, although it is less pronounced than in the CIV line. Clavel (1991) found that the fractional variation of the wing flux is as large as that of the continuum, whereas the flux in the core only changes by $\sim 50\%$.

Changes in the model profile which affect only the red side of the line or the red side before the blue can only be a result of changes in the transmittance or the reflectance of the disc. In general, if there are no structural changes we expect continuum variations to produce simultaneous changes in the red and blue wings, if we include reflection from the disc, and for changes on the blue side to precede those on the red if there is no reflection. Since the unreflected line is asymmetric and the reflected component contributes a higher fraction to the red than the blue the relative changes in the wings can be complex. The fractional changes in the wings will also depend on the continuum pulse length, because of the extra path length for the reflected component from the outer clouds.

Fig. 6 shows the transfer function for the CIV line as a whole. We have also constructed a diagram for the core of the line (±3000 km s^{-1}) only. The variation in the core provides between .03 and .1 of the peak throughput; the remainder is provided by the wings so the fractional change in the wings must exceed that in the core.

The core of CIV responds to UV variations with a delay of 6.5±3 days, significantly longer than the response time of the wings which is 3.2±3 days on average (Clavel 1991).

The 1d model transfer functions for the wings and line core separately show that the bulk of the core lags the wings in response to UV continuum changes.

4.8 Optical lines

Antonucci & Cohen (1983) observed that part of the Hβ line flux responded to continuum changes immediately, but a large part responded only gradually. Most or all of the flux of the higher-series Balmer lines and the λ4686 line of HeII responded immediately. They observed no gross profile changes. Also, the features of the Hβ profile are very similar in 1981 and 1975, through high

and low states. In the first half of 1984, while the nucleus was in a low state, De Robertis (1985) observed little, if any, broad Hβ and very weak broad Hα emission.

Comparisons between Hβ and CIV show that CIV is much broader than Hβ (Osterbrock & Koski 1976); this is especially evident in the low luminosity state. The change in Hβ between the high state and the low state was found to be qualitatively similar to that of the CIV profile (Ptak & Stoner 1985). The Lyα/Hβ ratio is of order 11.6 (Ferland & Mushotzky, 1982), much higher than typical for active galaxies; the intrinsic value could be even higher since the blue side of the Lyα line is missing (Penston et al. 1979, Ferland & Mushotzky 1982). Boksenberg & Shortridge (1975) observed that the HeI $\lambda\lambda$5876 and 7065 lines are twice the width of the Balmer line wings.

Observations by Lyutyi (1976) show that the Hα + [NII] emission feature varies in intensity with a 30-d lag for the 1970-72 period and 60-70 days in 1973-76. Maoz et al. (1991) have observed a lag in the Balmer lines of 9$\pm$2 days, still significantly longer than the UV line lags.

For the dense inner BLR clouds with our high ionisation parameter we find that the Balmer lines, are suppressed relative to CIV (For Hα this is clear from Table 1.) Thus the ILR is a significant contributor to the Balmer lines. This is consistent with the relative line widths, ratios and time lags. At lower luminosity the BLR contribution is relatively less important for the CIV line, reducing the CIV/Hβ ratio and giving lines that differ less in width.

4.9 Continuum

Clavel et al. (1990) found that in the UV the typical amplitude of variability was the same at 1715$\AA$ and 1455$\AA$ but there did appear to be some spectral variations which preceded the changes in flux levels by about 12 days. The ratio of maximum to minimum flux was 3.1 for the continuum at 1455$\AA$ but only 1.24 at 5000$\AA$. The continuum below 1900$\AA$ underwent small but significant spectral variations. (Clavel et al. 1990). The X-ray luminosity in the 2-10 keV band has been found to vary between $\sim 2 - 20 \times 10^{42}$ erg s^{-1} (Yaqoob et al. 1993). The spectral variations are complex but consistent with a picture of an intrinsically variable source, with a spectrum that steepens on brightening. This is seen through an absorbing column that has been modelled as cold ($T < 10^5$K) gas that partially covers the source and varies on time scales of months to years within a range of column densities $N_H \sim 5 - 15 \times 10^{22}$ cm^{-2} (Barr et al. 1977, Pounds et al. 1986, Yaqoob et al. 1989) or as warm gas where the soft X-ray opacity is reduced by partial ionization (Warwick & Done 1994, see also Weaver et al. 1994). The depth of the iron K-edge implies an iron overabundance of order twice solar. There is very little reddening of the optical continuum with A$_v \approx 0.2$ (Mushotzky et al. 1978). Therefore the X-ray absorption is not due to dust.

We have taken the spectral shape to be independent of luminosity state. In

fact, modest changes in spectrum do not appear to alter qualitatively any of the conclusions of the paper.

We note the possible connection between our BLR model and the X-ray observations. From fig. 1 we see that if the X-ray source is located centrally then there will be some absorption from the ILR and BLR clouds in the line of sight. The ILR is a candidate for the fixed component of the absorbing screen (Yaqoob et al. 1989) with the BLR clouds forming a variable partial coverer. Yaqoob et al. (1991) excluded the warm absorber model for this source, although Weaver et al. (1994) include a warm absorber in a two component picture. In our model the X-ray source must be partially covered but there could be also a scattered component and possibly some absorption from the warm cloud debris. The lack of reflection features from a disc (Maisack and Yaqoob 1991) is another indication that the angle to the line of sight is closer to edge-on than face-on. The complex absorption cut-off observed by Ginga is also difficult to understand unless the line of sight is closer to being edge-on than face-on (Yaqoob 1993). This provides some support for the geometry of our model.

5 Conclusions

We began by constructing a theoretical model for the injection and dynamics of clouds in the broad and intermediate emission line regions. In this model the BLR clouds arise from the interaction between a nuclear wind and the radiatively heated disc surface and the ILR clouds form from the interaction of the wind with a thermally driven outflow from the disc. When applied to NGC 4151 we found we could specify a complete set of parameters fairly tightly from the profile of the CIV λ 1549 line in the high luminosity state of the nucleus. In particular the density of the inner clouds is high ($\sim 10^{12}$ cm^{-3}) and the region is small (10^{16} cm $< r < 10^{17}$ cm). From this and the assumption that the power in the wind drops strongly with decreasing radiative power, we derived profile fits to CIV in some intermediate luminosity states and accounted for the profile widths of other UV lines and the Balmer lines in various states. From the low luminosity state behaviour we deduced the existence of an extended intermediate line region with cloud densities $\leq 10^8$ cm^{-3}. This picture agrees with that derived from the transfer function and correlation analysis of the response of the lines to continuum variability. Provided we include reflection from the disc in constructing the line response then the model is also in qualitative agreement with what is known of the transfer function (the relative responses of red and blue wings and line core). The geometry deduced from our model BLR also leads us to suggest an interpretation of the X-ray absorption data to which we shall return in more detail elsewhere.

Of other possible models for NGC 4151 pure disc motion appears to be ruled out since variations in the line core would then *precede* that in the wings. In the Mathews model of oscillating clouds (Mathews 1993) the reponse of the core

and wings should be *simultaneous*, which it is probably not. In the picture of Dyson and Perry (1985) it is difficult to see how the red and blue wings of the line profiles could change simultaneously in a spherical outflow. A biconical model could be made to fit the available data for NGC 4151, but this would probably require us to treat this galaxy as an exception since the 2D transfer function of NGC 5548 (Horne et al. 1991) appears to exclude a biconical model for that galaxy.

In our model NGC 4151 is a 'special' case only in as much as we require a particular orientation to the line of sight. We shall show elsewhere that essentially the same model can be constructed for NGC 5548, except that the line of sight is at greater inclination to the disc. We shall also show how NGC 4151, which is usually regarded as an exceptional case, can be fitted into a unified picture for active galaxies.

6 Acknowledgements

We thank C.Done and R.S.Warwick for discussions on the X-ray properties of NGC 4151 and an anonymous referee for constructive comments.

References

Alexander, T. & Netzer, H., 1994, MNRAS, 270, 781
Anderson,K.S., Kraft, R.P., 1969, Astrophys. J., 158, 859
Antonucci, R.R.J., Cohen, R.D., 1983, Astrophys. J., 271, 564
Aretaxaga, I. & Terlevich, R., 1994, MNRAS, 269, 462
Barr, P., White, N.E., Sanford, P.W., Ives, J.C., 1977, MNRAS 181, 43P
Begelman, M.C., McKee, C.F., Shields, G.A., 1983, Astrophys. J., 271, 70
Blandford, R.D.& McKee, C.F., 1982, Astrophys. J., 255, 419
Blumenthal, G.R.& Mathews, W.G., 1975, Astrophys. J., 198, 517
Boksenberg, A., Shortridge, K., 1975, MNRAS, 173, 381
Capriotti, E., Foltz, C. & Byard, P., 1980, Astrphys. J., 241, 903
Carroll, T. & Kwan, J., 1985, Astrophys. J., 288, 73
Cassidy, I., Raine, D.J., 1993, MNRAS, 260, 385
Cassidy, I., 1994, PhD Thesis, University of Leicester
Chandrasekhar, S., 1961, Hydradynamic and Hydromagnetic Instability, Oxford University Press, p. 483
Clavel, J., Altamore, A., Boksenberg, A., Bromage, G.E., Elvius, A., Pelat, D., Penston, M.V., Perola, G.C., Snijders, M.A.J., Ulrich, M.-H., 1987, Astrophys. J., 321, 251
Clavel, J., Wamsteker, W., 1987, Astrophys. J., 320, L9
Clavel J., Boksenberg, A., Bromage, G.E., Elvius, A., Penston, M.V., Perola, G.C., Santos-Lleo, M., Snijders, M.A.J., Ulrich, M.-H., 1990, MNRAS, 246, 668

Clavel, J., 1991, Variability in Active Galactic Nuclei, eds. H.R. Miller, P.J. Wiita, Cambridge University Press, p. 301
Collin-Souffrin, S., 1987, Astron. Astrophys., 179, 60
Collin-Souffrin, S., Dyson, J.E., McDowell, J.C., Perry, J.J., 1988, MNRAS, 232, 539
Crenshaw, D.M., Peterson, B.M., Wagner, R.M., 1988, Astron. J., 96, 1208
Cromwell, R., Weyman, R., 1970, Astrophys. J., 159, L147
Czerney, M. & King, A.R., 1989, MNRAS, 241, 839
Emmering, R.T., Blandford, R.D., Schlosman, I., 1991, Astrophys. J., 385, 460
Evans et al., 1993,
Fahey, R.P., Michalitsianos, A.G., Kazanas, D., 1991, Astrophys. J., 371, 136
Ferland, G.J., Mushotzky, R.F., 1982, Astrophys. J., 262, 564
Filippenko, A.V., 1991, Physics of Active Galactic Nuclei, eds. W.J. Duschl, S.J. Wagner, Springer Verlag, p. 345
Gaskell, C.M., 1988, Astrophys. J., 325, 114
Krolik, J., 1991, Physics of Active Galactic Nuclei, eds. W.J. Duschl, S.J. Wagner, Springer Verlag, p. 173
Krolik K.J., McKee, C.E. & Tartar, C.B., 1981, Ap.J., 249,422
Loska, Z., Czerny, B., Szczerba, R., 1993, MNRAS 262, L31
Lyutyi, V.M., 1976, Soviet Astronomy, 21, 655
Maisack, M. & Yaqoob, T.,1991, Astron.Astrophys., 249, 25
Mathews, W.G. & Doane, J.S., 1990, Astrophys. J., 352, 423
Mathews, W.G., 1993, Astrophys. J., 412, L17
Maoz et al., 1991, Astrophys. J., 367, 493
Mobasher, B. & Raine, D.J., 1989, MNRAS, 237, 979
Mobasher, B. & Raine, D.J., 1990, MNRAS, 244, 652
Mushotzky, R.F., Holt, S.S., Serlemitsos, P.J., 1978, Astrophys. J., 225, L115
Nandra, P. & Pounds K.A., 1994, MNRAS, 268, 405
Netzer, H., 1991, Active Galactic Nulcei, eds. R.D. Blandford, H. Netzer, L. Woltjer, p. 57
Oke, J.B., Readhead, A.C.S., Sargent, W.C.W., 1980, PASP, 92, 758
Osterbrock, D.E., Koski, A.T., 1976, MNRAS, 176, 61P
Penston, M.V., Clavel, J., Snijders, M.A.J., Boksenberg, A., Fosbury, R.A.E., 1979, MNRAS 189, 45P
Penston, M.V. et al.,1981, MNRAS 196, 857
Penston, M.V., 1991, Variability of Active Galactic Nuclei, eds. H.R. Miller, P.J. Wiita, Cambridge University Press, p. 343
Perez, E., Robinson, A., de la Fuente, L., 1992, MNRAS, 256, 103
Perola G.C. et al., 1982, MNRAS, 200, 293
Perry, J.J., Dyson, J.E., 1985, MNRAS, 213, 665
Peterson, B.M., 1988, PASP, 100, 18
Ptak, R.L., Stoner, R., 1985, Bull. AAS, 17, 846
de Robertis, M., 1985, Astrophys. J., 289, 67
Robinson, A., 1995, MNRAS, 272, 647

Shields, G.A., 1978, Proc. Pittsburgh Conf. on BL Lac Objects, ed. A.M.Wolfe, p. 257
Smith, M.D., Raine, D.J., 1984, MNRAS, 212, 425
Smith, M.D., Raine, D.J., 1988, MNRAS, 234, 297
Snijders, M.A.J., 1990, Variability of Active Galaxies, Proceedings Heidelberg, eds. W.J. Duschl, S.J. Wagner, M. Camenzind
Stoner, R.E., Ptak, R., 1986, New Insights in Astrophysics, ESA SP-263, p. 605
Ulrich, M.-H., Boksenberg, A., Bromage, G.E., Clavel, J., Elvius, A., Penston, M.V., Perola, G.C., Pettini, M., Snijders, M.A.J., Tanzi, E.G., Tarenghi, M., 1984, MNRAS 206, 221
Ulrich, M.-H.,1986, Structure and Evolution of Active Galactic Nuclei, eds. G. Giuricin et al., Dordrecht: Reidel, p. 275
Ulrich, M.-H., Boksenberg, A., Bromage, G.E., Clavel, J., Elvius, A., Penston, M.V., Perola, G.C., Snijders, M.A.J., 1991, Astrophys. J., 382, 483
van Groningen, E., de Bruyn, A.G., 1989, Astron. Astrophys., 211, 293
Warwick, R.S. & Done, C., 1994, unpublished
Weaver, K.A., et al. 1994, Ap.J., 423, 621
Yaqoob, T., Warwick, R.S., Pounds, K.A., 1989, MNRAS 236, 153
Yaqoob, T. & Warwick, R.S., 1991, MNRAS, 248, 773
Yaqoob,T.,Warwick, R.S., Makino, F., Otani,C., Sokoloski, J.L., Bond, I.A., & Yamauchi, M.,1992, MNRAS, 262, 435
Yee, H.K.L.& Oke, J.B., 1981, Astrophys. J., 248, 442
Zheng, W., Binette, L. & Sulentic, J.W., 1990, Astrophys. J., 365, 115

Figure Captions

Fig. 1 Sketch of the line emission regions of NGC 4151. The BLR lies between r_{in} and r_{out} in a region of the disc dominated by external illumination where strong Kelvin-Helmholtz instabilities at the interface with the nuclear wind, labelled v_w, lead to cloud formation and entrainment. The ILR lies between r_{ic} where Compton heating is sufficient to drive material from the disc and r_{iso} where the heating timescale exceeds the escape time. The disc is probably optically thick at small radii and thin at large radii; various assumptions are explored in the text.

Fig. 2. The observed high state CIV profile (solid line) compared with the model profile for a disc of zero albedo which partially covers clouds on the far side (dotted line) and for a disc with an albedo of 0.3 with clouds on the far side totally obscured (dashed line). The model lines have been scaled vertically to give the best fit. Velocities on the horizontal axis are given in km s^{-1} with negative velocities to the red.

Fig. 3. The effect of changing disc obscuration. The solid line is for a disc which obscures totally at distances $\leq 5 \times 10^{16}$ cm and the dashed line, on the same vertical scale, is for total obscuration at $\leq 1 \times 10^{16}$ cm. The dotted line is the profile difference. From the symmetry of the model these profiles effectively show also the effect of increasing albedo (from 0 to 1 in the region 1×10^{16}cm to 5×10^{16}cm).

Fig. 4. A sequence of 3 CIV model profiles, on the same vertical scale, from high to intermediate states. The profile narrows as the acceleration of clouds by the wind decreases corresponding to decreasing luminosity states.

Fig. 5 CIV profile fit for the low luminosity state. The observed profile is shown as the solid line, the BLR contribution is the dot-dashed line, scaled vertically to fit the bulk of the line outside the core, and the difference is the dashed line. The difference profile is the contribution from the ILR in the model.

Fig. 6 One dimensional model transfer function for the CIV line (a) in a low-luminosity state ($l_r = 0.01$, dashed line) and (b) in a high state ($l_r = 0.1$, solid line). The number of half day intervals is marked on the x-axis.

Fig. 7 Two dimensional model transfer function for the CIV line (with a partially obscuring disc and zero albedo). The time is given in half-day intervals and the velocities in km s^{-1}.

Fig. 8 Two dimensional model transfer function for the component of the CIV line reflected by a disc with constant albedo. The time is given in half-day

intervals and the velocities in km s^{-1}.